Low-Temperature Gasoline Combustion (LTGC) Engine Research

Project ID: ACE004

John E. Dec

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June 11, 2019 – 4:00 p.m.

U.S. DOE, Office of Vehicle Technologies
Annual Merit Review and Peer Evaluation

Program Managers: Gurpreet Singh & Michael Weismiller

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

- Project provides fundamental research to support DOE/Industry advanced engine projects.
- Project directions and continuation are evaluated annually.

Barriers / Research Needs

- Technologies for rapid combustion-timing control for LTC engines
- Improved low-load operation and combustion efficiency
- Effects of advanced fuel-injection strategies (e.g. multiple injections), and tailored fuel-air stratification
- Improved simulation tools for advanced LTC processes
- Improved cold-start technologies for LTC

Budget

- Project funded by DOE/VT:
- FY18 – $675k
- FY19 – $750k

Partners / Collaborators

- Project Lead: Sandia ⇒ John E. Dec
- Advanced Engine Combustion MOU: 15 industrial partners
- Cummins – Hardware
- GM – Hardware & Discussions
- HATCI – Hyundai-Kia America Tech. Cntr.
- LLNL – Kinetic Modeling
- ANL – CFR-engine data and Autonomie
- SUNY-Stony Brook – CFD Modeling
- U-Conn – Skeletal mechanism for CFD

- Co-Optima Fuels proj., separately funded
- Chevron, Funds-in – Adv. fuels for LTGC

Relevance/Objectives – 1

Relevance

- **Low-Temperature Gasoline Combustion (LTGC) engines can provide diesel-like or higher efficiencies with very low NOx & PM.**
- **Our LTGC method** ⇒ kinetically controlled compression ignition (CI) of a dilute charge with well-controlled low-to-moderate stratification that varies with operating condition. LTGC includes HCCI & stratified HCCI-like comb.
- LTGC research is relevant to:
  1) <u>Multi-mode operation for LD</u>, use LTGC up to ~10 bar IMEP for high efficiency, then switch to boosted SI for high loads.
  2) <u>Full-time LTGC for MD/HD</u> ⇒ Same strategies as LD for IMEPg ≤ 10 bar. Loads up to 20 bar IMEPg have been achieved with ultra-low NOx and PM and no knock, max. $P_{cylinder}$ = 150 bar.
- Several potential advantages for MD/HD:
  1) Efficiencies can modestly exceed those of diesel engines
  2) Lower cost fuel-injection equipment ⇒ GDI-type 300 – 600 bar
  3) Reduced aftertreatment costs for NOx and PM, much less DEF.
  4) Would help balance demand for gasoline and diesel fuel ⇒ Potentially lower fuel costs for customer

Relevance/Objectives – 2

Project Objectives

1) **Provide the fundamental understanding (science-base) required for the development practical LTGC engines by industry.**
2) **Explore methods to exploit this understanding to overcome the technical barriers to LTGC.**

FY19 Objectives:

- Expand our understanding of the operating & control range for our new additive-mixing fuel injection (AMFI) system.
- Investigate the use of partial fuel stratification produced by double injections (DDI-PFS) to control autoignition at naturally aspirated & low-boost conds.
- Collaborate with SUNY-Stony Brook to conduct CFD modeling to better understand the mixture formation with DDI-PFS.
- Complete a study of the chemistry of ϕ-sensitivity, its relationship to octane-sensitivity, and implications for fuel composition.
- Continue collaborations with LLNL to validate and improve kinetic models.
- Modify new cylinder head for optical engine (match current metal-engine head).

Approach

Overall Technical Approach

- Combine metal- and optical-engine experiments, analysis and modeling to build a comprehensive understanding of LTGC fundamentals.
- Extend this understanding to develop and evaluate methods that can overcome the technical barriers to LTGC.
- Collaborate with other institutions to leverage complementary capabilities and share expertise.
- Transfer results to industry.

<u>Detailed approaches for main objectives</u>

- Combustion-timing control & greater operating range – relevant to LD & MD/HD
  - AMFI system:
    $\Rightarrow$ Further investigate capabilities $\Rightarrow$ effects of T_{in}, EGR, and <u>potential for low loads</u>.
    $\Rightarrow$ Investigate the potential of making a new design for faster control.
  - DDI-PFS can also provide CA50 control $\Rightarrow$ investigate its capabilities for a wide range of conditions and its potential for controlling CA50 through a load sweep.
  - Initiate ability to study transients $\Rightarrow$ first step, establish a closed-loop control system.
- CFD modeling can support and extend experiments
  - Investigate the potential of LES-CFD to predict LTGC performance for DDI-PFS.
  - Collaborate with SUNY to apply LES-CFD & with U. Conn to a develop skeletal mech.

Milestones and Project Goals

- ✓ **August 2018**
  Determine potential of the new control device to extend the low-load limit and for cold start. Give AEC presentation on combined studies with new control device.

- ✓ **January 2019**
  Complete initial study of DDI-PFS with variations in DI-timing and fuel-fraction split between injections to control CA50 w/ acceptable NOx at naturally aspirated and low-boost conditions.

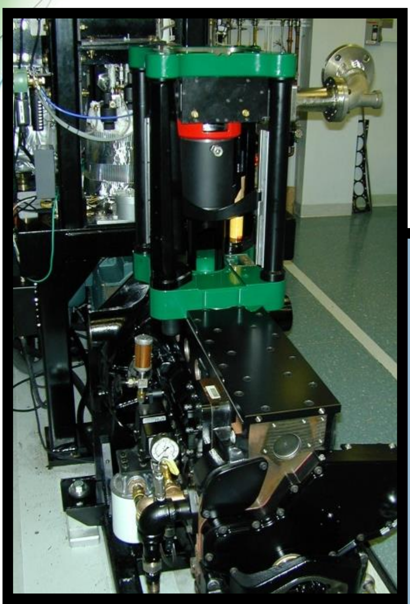
- ✓ **April 2019**
  Establish a closed-loop control system for LTGC using the new additive-based control device & demonstrate automated CA50 control through a load change.

- ✓ **June 2019 – Formal Milestone**
  Complete study of ϕ-sensitivity, octane sens., & development of fuel blends to enable CA50 control using fuel stratification: SAE 2019-01-0961 for WCX-2019

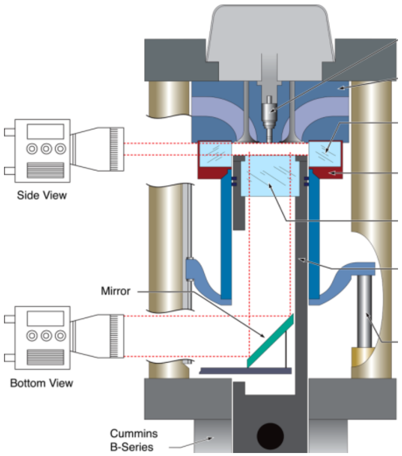
- **September 2019 – Formal Milestone**
  Characterization of the operating and control range of the additive–based control strategy system – publication or presentation.

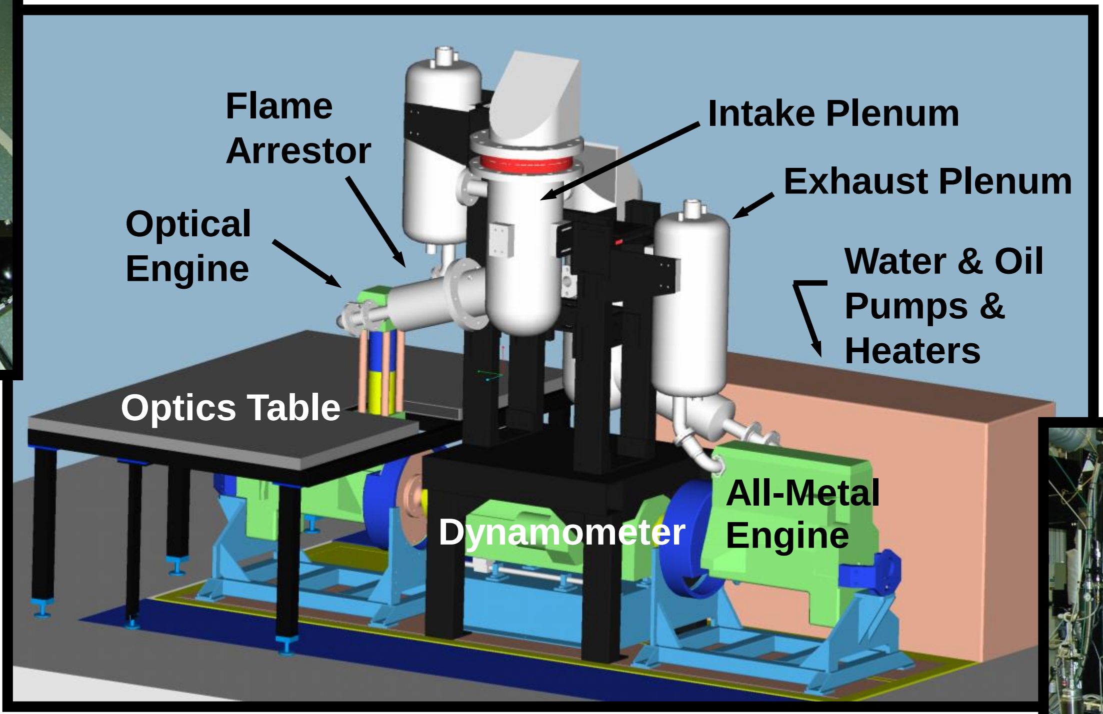
Sandia LTGC Engine Laboratory

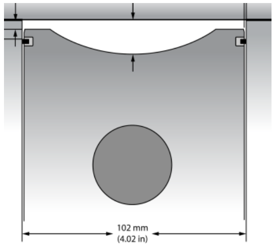
- Matching all-metal & optical LTGC research engines.
  - Single-cylinder conversion from Cummins B-series Medium-Duty diesel.



Optical Engine

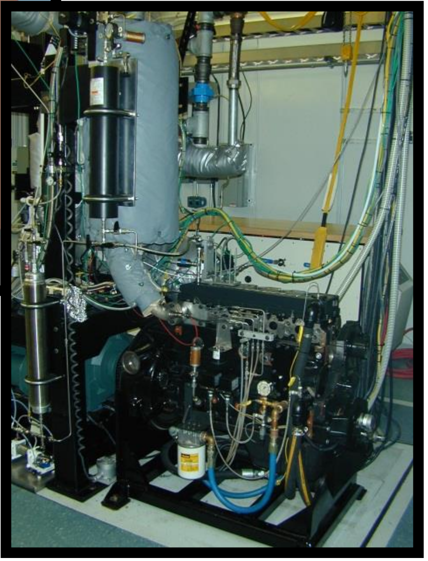






Open-chamber LTGC piston CR = 14:1

All-Metal Engine



- Bore x Stroke = 102 x 120 mm
- 0.98 liters, CR = 14:1 (adjustable)
- **GDI fuel injector** & fully premixed fuel system
- Spark-plug capable
- Independent control of most engine parameters

Overview of Accomplishments

- AMFI control system:
  1) Determined the effects of changes in T_{in} and EGR.
  2) Applied AMFI with single-DI stratification to extend operation to low loads ⇒ achieved IMEPg = 2 bar with a Thermal Eff. = 37%.
  3) Developed a new design for faster control.
- DDI-PFS for CA50 control – Investigated effects fuel-fraction split between injections, equivalence ratio (ϕ), P_{in} & T_{in} for both straight and additized fuel.
  - Demonstrated DDI-PFS control for a ~30% load change, maintaining low NOx.
- Collaborated with SUNY–Stony Brook to apply LES-CFD to understand changes in mixture formation with DDI-PFS, & validated overall performance.
- Collaborated w/ U. Conn. to develop & validate a skeletal mech. for LES-CFD.
- Developed a closed-loop control system and demonstrated control with AMFI.

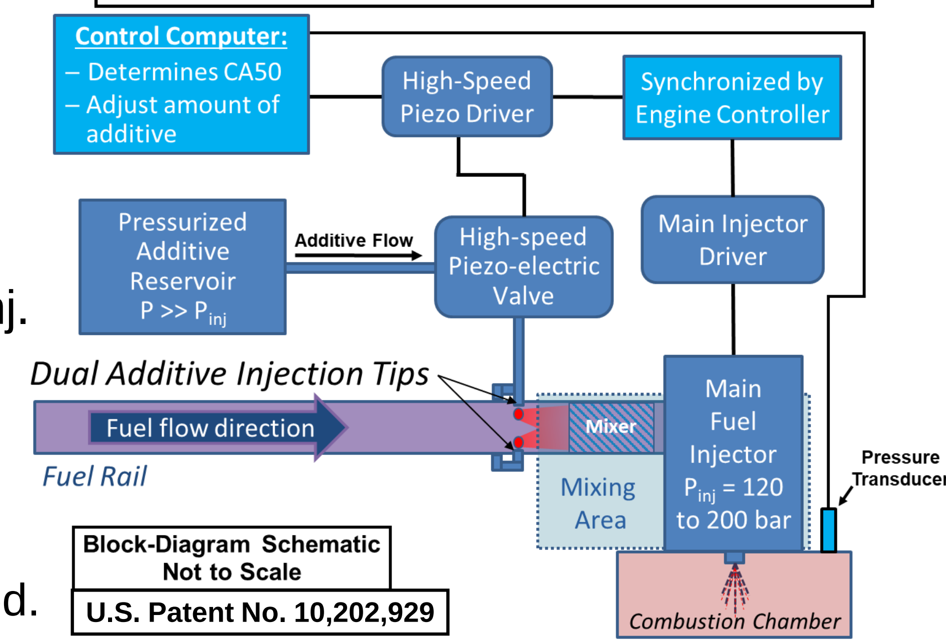
Additional accomplishments – Not presented due to time limitations

- Completed a study of the chemistry causing ϕ-sensitivity & how this can lead to a potentially more optimal fuel for LTGC & mixed-mode ⇒ SAE 2019-01-0961.
- Collaborated w/ LLNL to test their kinetic mech. and added reactions for EHN.
- Modified new cylinder head for optical engine – on track for completion FY19.
- **Establishing a collaboration with Hyundai-Kia** on their LTC-engine project.

Review of AMFI Control System

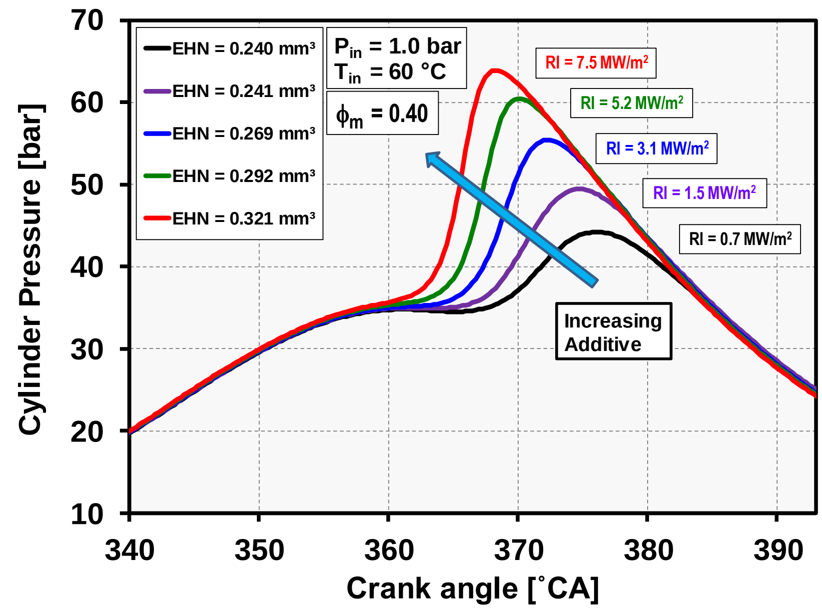
- Combustion-timing control is perhaps the most challenging barrier to practical LTGC & HCCI-like engines
- Last year we introduced a new control technique that is robust w/ inherent potential for control through rapid transients. ⇒ Additive-mixing fuel-injection (AMFI) system.
  - AMFI can also significantly reduce the heating/hot-residuals required for autoignition.
- Uses a high-speed piezo-electric valve to meter a controlled amount of ignition enhancing additive each engine cycle ⇒ tenths of mm^3 with high precision.
- Additive currently used is 2-ethylhexyl nitrate (EHN), but others are available.
  - Estimate **~gallon-sized reservoir ~7000 mi. cost ~$20 to save $150 of gasoline.**
- Currently, additive is introduced close to fuel injector.
  - In a commercial application might be incorporated into the fuel injector.
- Additive injection synchronized w/ fuel inj. for improved mixing and time response.
- AMFI system is well-suited for closed-loop control to maintain desired CA50 through transients.
  - Initial closed-loop control recently tested.

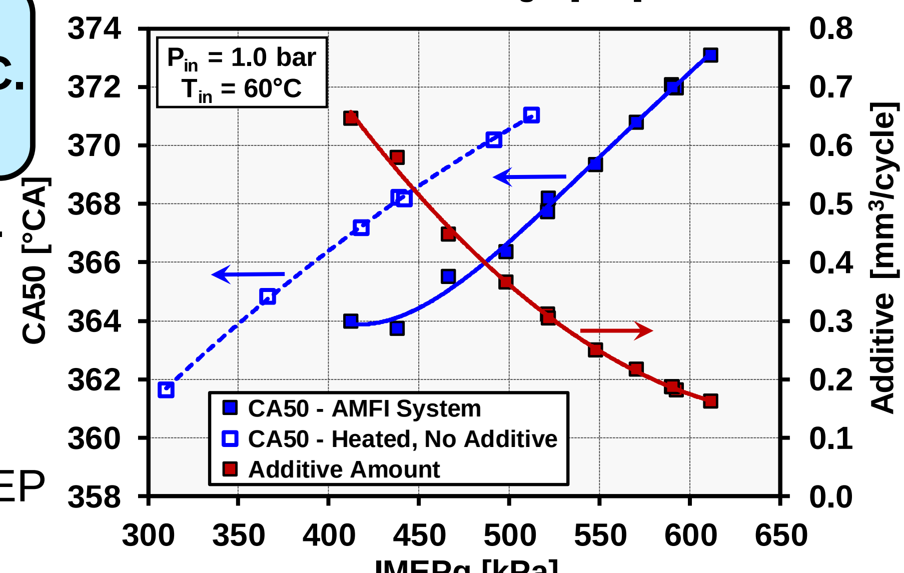
Block Diagram of AMFI Control System



Review – AMFI Provides Robust CA50 Control

- Additive enhances autoignition, reducing or eliminating need for intake heat or hot-residuals. **Selected T_{in} = 60°C.**
- Adjusting the additive easily shifts CA50 from very retarded (near misfire) to overly advanced (knocking), **in a few seconds**. ⇒ Near next-cycle should be possible.
- W/O additive, heat T_{in} & adjust 149 – 158°C for same CA50 variation ⇒ very slow.
- AMFI controls CA50 well through a fueling sweep, $0.3 \le \phi \le 0.46$, **constant T_{in}= 60°C.**
  - AMFI can quickly adjust CA50 as req'd.
- W/O additive, adjust T_{in} from 144 - 181°C.
- The lower T_{in} with AMFI system also:
  - Increases charge density ⇒ 20 – 30% higher IMEPg for same range of ϕ.
  - ➚Thermal Eff. 44.5 to 46.1% at 5 bar IMEP ⇒ CR = 14:1, higher TE at CR = 16:1

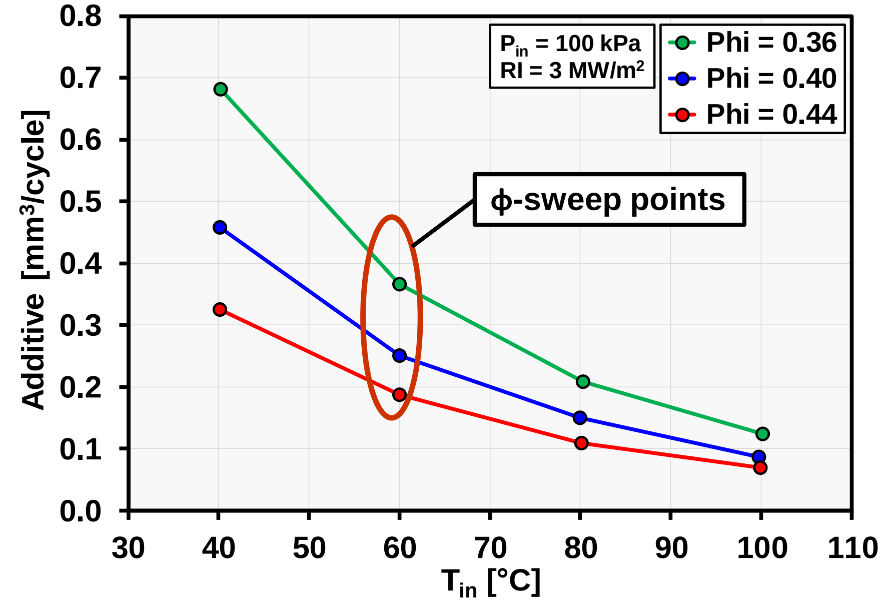


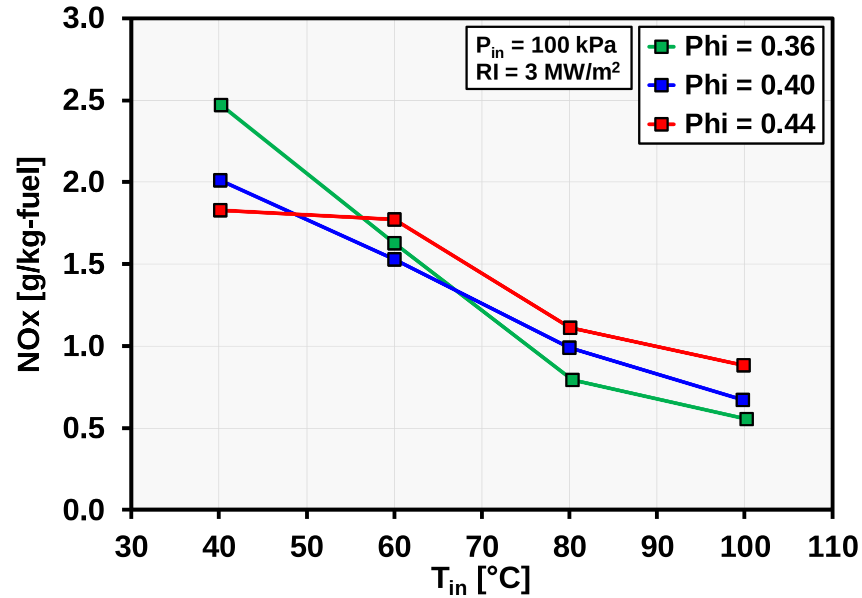


- **AMFI controls well through load sweep ⇒ also speed & boost sweeps.**

Begin New AMFI Investigations: Effects of Intake T_{in} on Additive Requirements

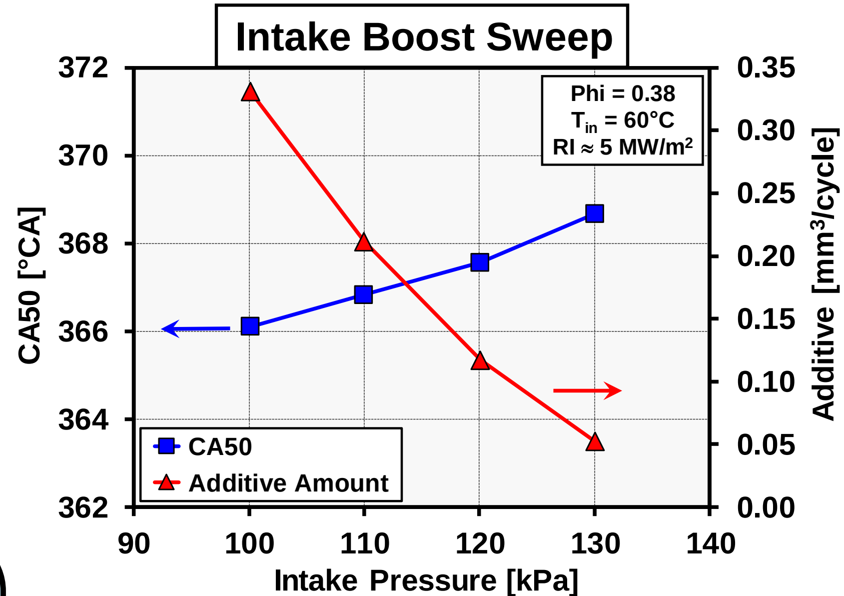
- Amount of additive required to maintain RI = 3 MW/m^2 decreases greatly as T_{in} is increased from 40 – 100°C.
  - Greater decrease at lower ϕ
  - Still enough additive for good control at T_{in} = 100°C ⇒ Need ≥ ~0.03 mm^3/cycle.
  - W/O additive 161 ≤ T_{in} ≤ 147°C
- Fuel specific NOx decreases with decreased EHN additive as expected. ⇒ Soot remains below detection limit.
  - Modest increase in thermal NOx at higher T_{in} for higher ϕs causes a reversal in the order of NOx vs. ϕ with ↗T_{in}.
- Heating can greatly reduce the required additive and NOx emissions. ⇒ **AMFI still gives good CA50 control.**
- Combining AMFI with modest heating at selected conditions could improve overall performance.

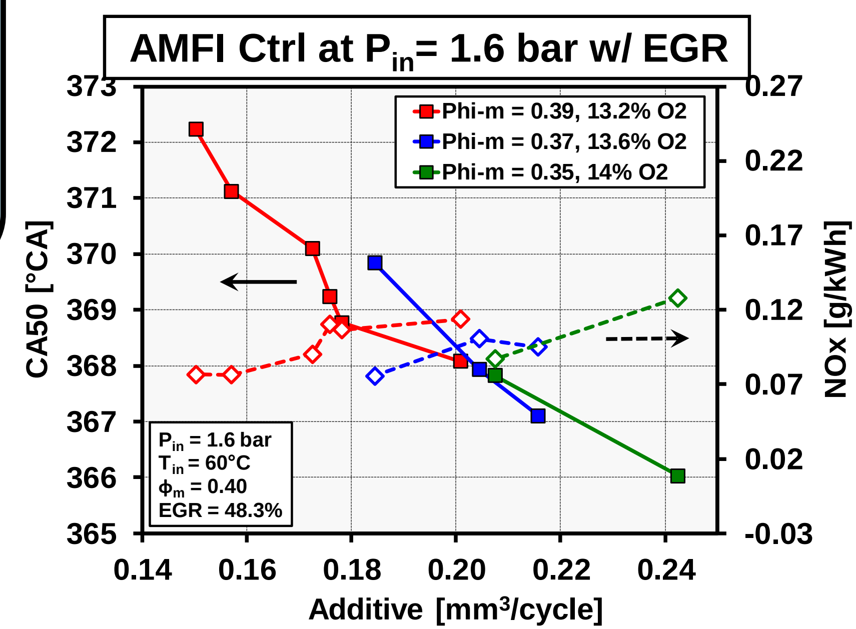




AMFI Control at Conditions with EGR

- Fuel reactivity increases with boost, so additive will approach zero at $P_{in} \approx 1.4$ bar. ⇒ Need EGR above this P_{in}.
  - Constant T_{in} = 60°C and RI = 5 MW/m²
- At P_{in} = 1.6 bar, EGR is required to prevent overly advanced CA50 even w/o additive (O_2 = 18% for RI = 5 MW/m²) ⇒ Must ↗EGR for AMFI to control CA50.
- Use EGR = 48.3% (13.2% O_2 at ϕ = 0.39) & apply AMFI to sweep CA50, RI = 2 to 7.
- AMFI system can control CA50 with changes in load, const. EGR = 48.3%.
  - ϕ = 0.39, 0.37, and 0.35 shown
- **AMFI can control CA50 and adjust for changes in load with EGR ⇒ similar to operation w/o EGR.**
- NOx emissions remain less than half of the US-2010 H-D limit of 0.27 g/kWh.



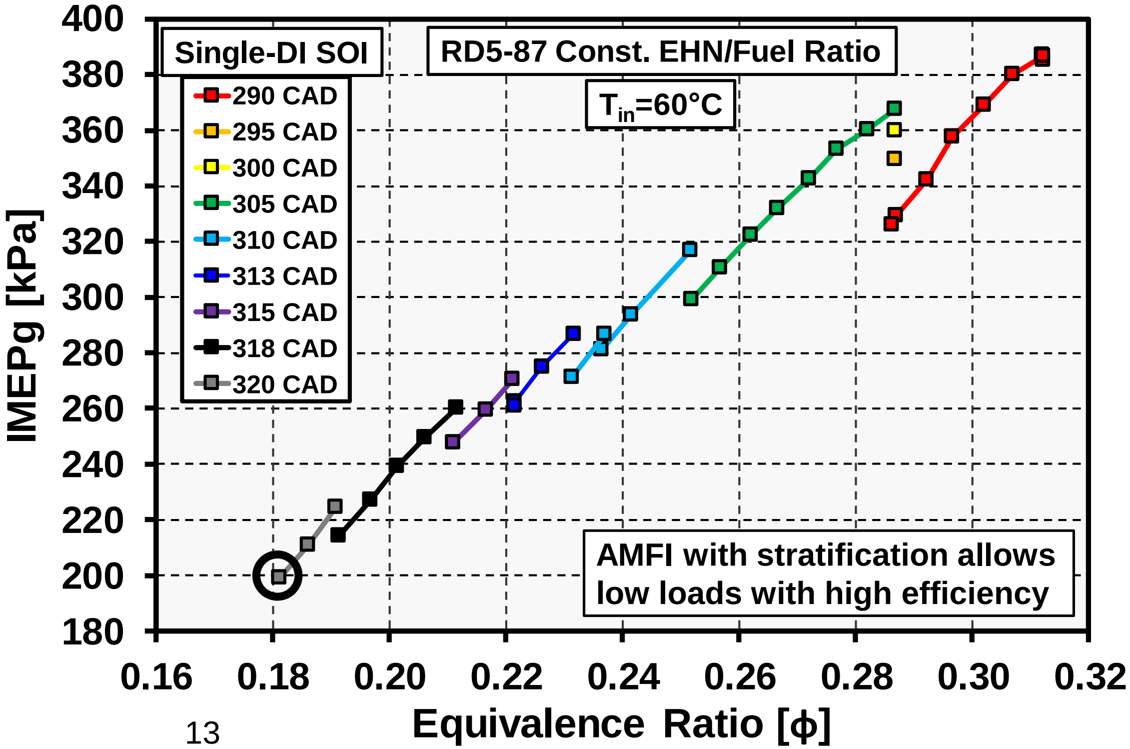


AMFI Allows Operation at Low Loads w/ T_{in} = 60°C

- Fuel stratification is required for good combustion eff. for loads < ~3.0 – 3.5 bar IMEPg ⇒ keep T-combustion ≥ 1500 K ⇒ SAE 2007-01-4130.
- Additive makes the fuel ϕ-sensitive (autoig. timing varies with local ϕ), allowing the advantages of PFS even at naturally aspirated & low-boost P_{in}s.
- With AMFI, this ϕ-sensitivity works with the stratification to enhance autoignition, allowing loads down to IMEPg = 2 bar with little or no heating, T_{in} = 60°C.
- Hold EHN/fuel ratio constant at value for ϕ = 0.3 with early-DI, presented earlier.
- Progressively **increase charge stratification with later <u>Single-DI</u> timings** as fueling is reduced ⇒ to maintain good combustion efficiency.

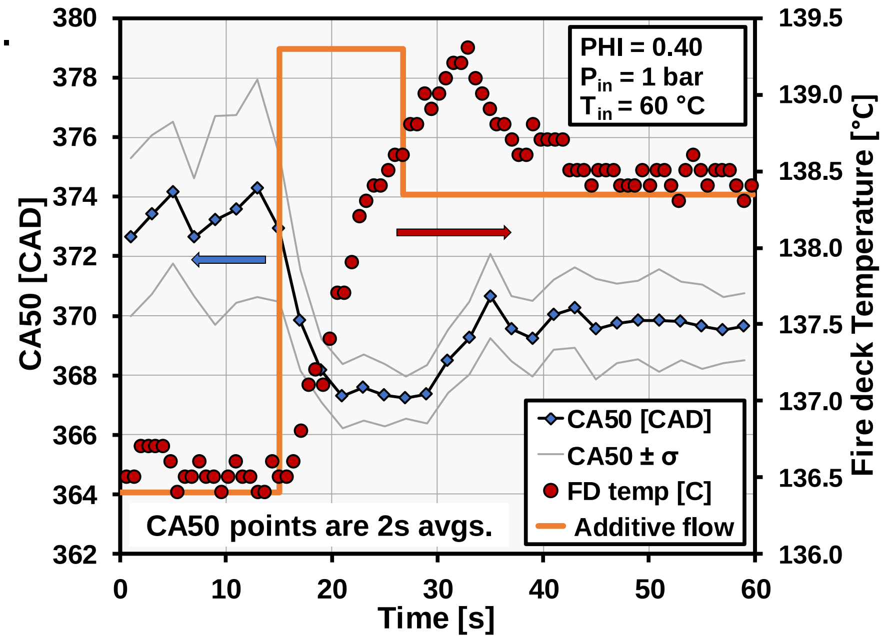
- Achieved IMEPg = 2 bar with 37% ind. thermal eff.
- Considerable scope for further improvement (expect ~40%)

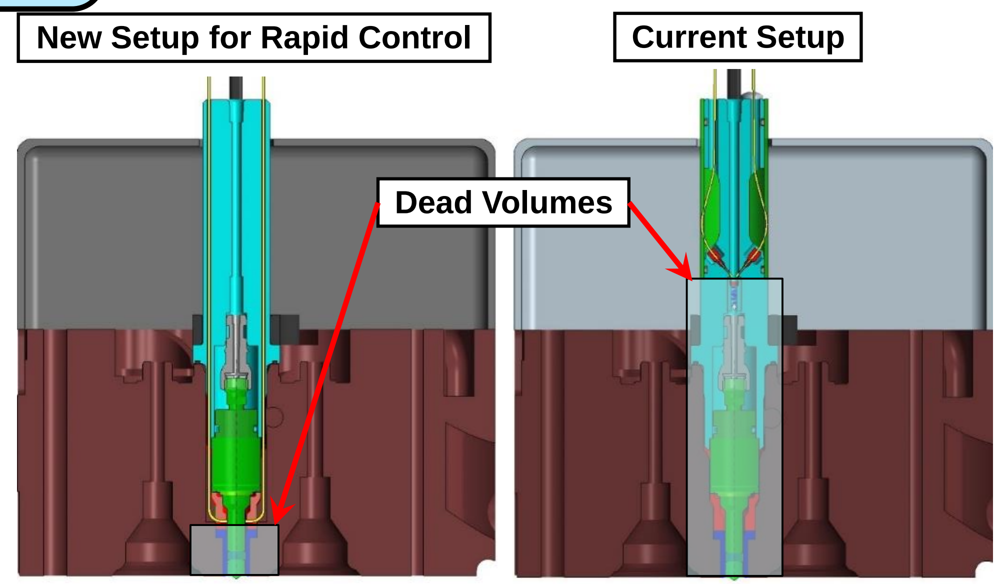
- **Cold start has also been demonstrated (20°C).**



Transient Response of AMFI System

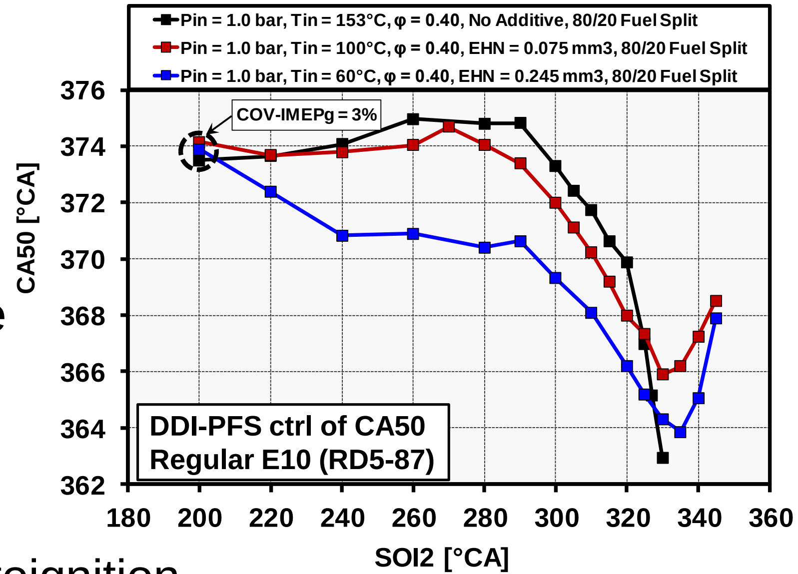
- Response time limited by fuel dead-volume. Current setup, estimate 2 to 3 secs
- Current setup for **initial proof-of-concept** to show AMFI can work.
  - Additive enters upstream of fuel injector.
- AMFI control itself is inherently very rapid ⇒ adjusts additive each engine cycle.
- Developing a new setup with reduced dead volume for much faster response.
  - Expect ~0.2 seconds vs. 2.5 seconds
- Also, AMFI is compatible with virtually all other control techniques ⇒ PFS, spark assist, EGR, NVO
- For example, could combine with DDI-PFS for next-cycle response over a moderate range ⇒ while AMFI extends for full range.
- In commercial application ⇒ work with injector manuf. build into inj.





CA50 Control Using DDI-PFS

- **<u>DDI-PFS</u>** (double-DI partial fuel stratification)
  - Inject 60 – 80% of fuel early, SOI1 = 60°CA
  - Inject remainder during compression stroke, SOI2 = 200 to ~320°CA to vary stratification.
- Richer regions ignite faster, if fuel is ϕ-sensitive
  - CA50 advances as SOI2 is retarded.
  - Works with or without additive
  - Control authority 8 – 10°CA

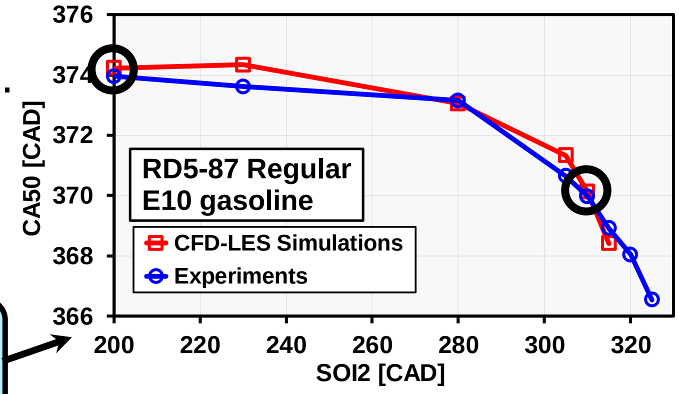


- To better understand mixture formation and autoignition timing, collaborate with SUNY-Stony Brook to apply LES-CFD:
  1) Can LES-CFD simulations explain this DDI-PFS behavior & change in CA50?
  2) SOI2 = 200°CA ⇒ Why is charge more well-mixed than with a single early-DI?
  3) SOI2 > 290°CA ⇒ Why does stratification/CA50-adv increase much more rapidly?

Simulating DDI-PFS Mixture Formation

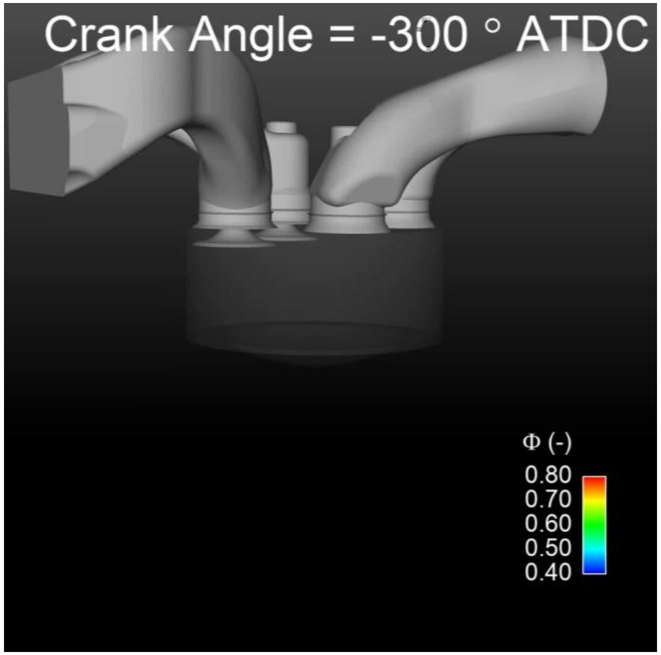
LES-CFD by SUNY-Stony Brook, Profs. S. Mamalis & B. Lawler

- Use CONVERGE LES simulations of DDI-PFS, but it required a reduced kinetic mechanism ⇒ none existed.
- SNL worked with U. Conn. to develop a new skeletal mechanism and surrogate for RD5-87, E10 gasoline.
  ⇒ Validated with expr. data & LLNL detailed mech.
- LES-CFD matches CA50 well over a range of SOI2s.
  ⇒ Gives confidence in the CFD and chemical kinetics.



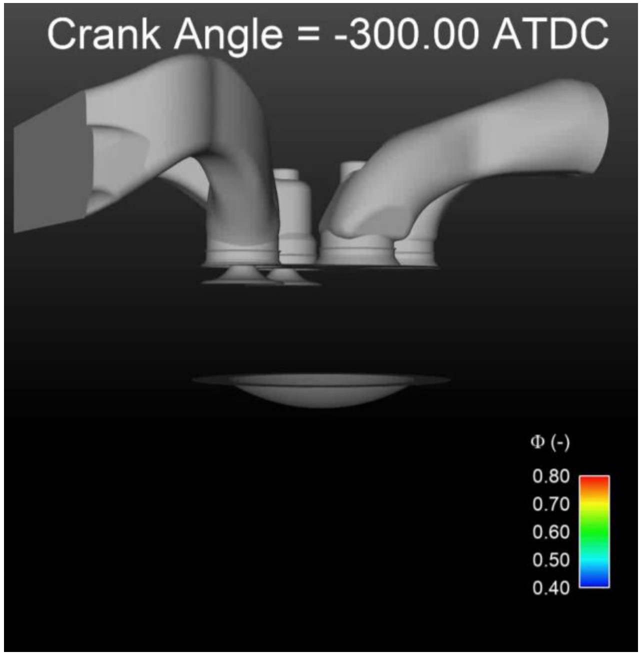
SOI_2 = 200 CAD

Iso-volumes of φ > 0.45



SOI_2 = 310 CAD

Iso-volumes of φ > 0.41



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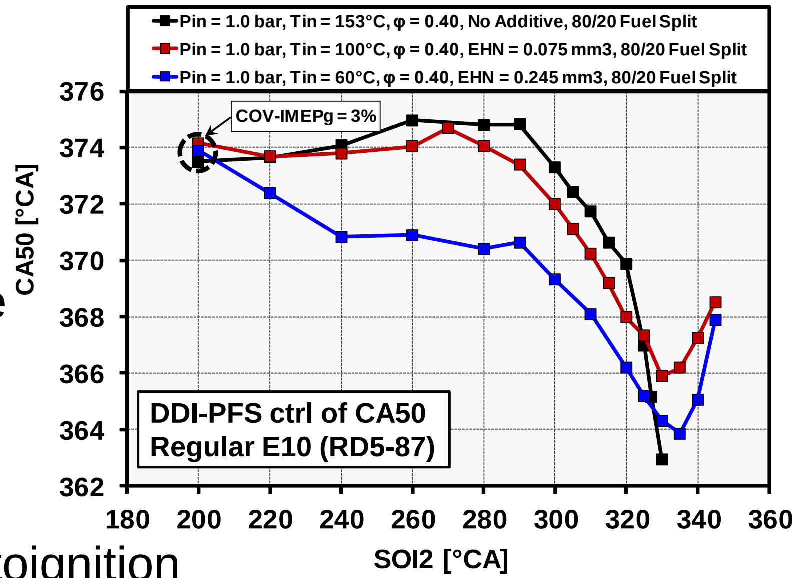

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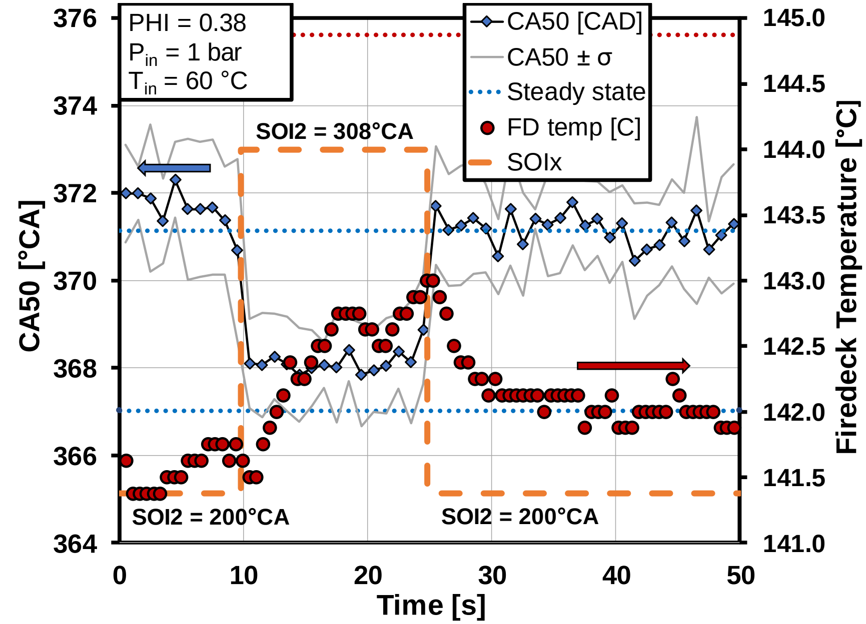
  2) SOI2 = 200°CA ⇒ Why is charge more well-mixed than with a single early-DI?
  3) SOI2 > 290°CA ⇒ Why does stratification/CA50-adv increase much more rapidly?
- LES-CFD with new skeletal mechanism shows:
  1) Simulations match CA50 well for a range of SOI2s.
  2) SOI2 = 200°CA ⇒ Fills in lean region in central part charge, more uniform mixture.
  3) SOI2 > 290°CA ⇒ 2nd injection deposits fuel in piston bowl, creating richer regions.
- **LES-CFD can help better-optimize fuel stratification, which has potential to significantly improve DDI-PFS for CA50 control and Single-DI for low loads.**

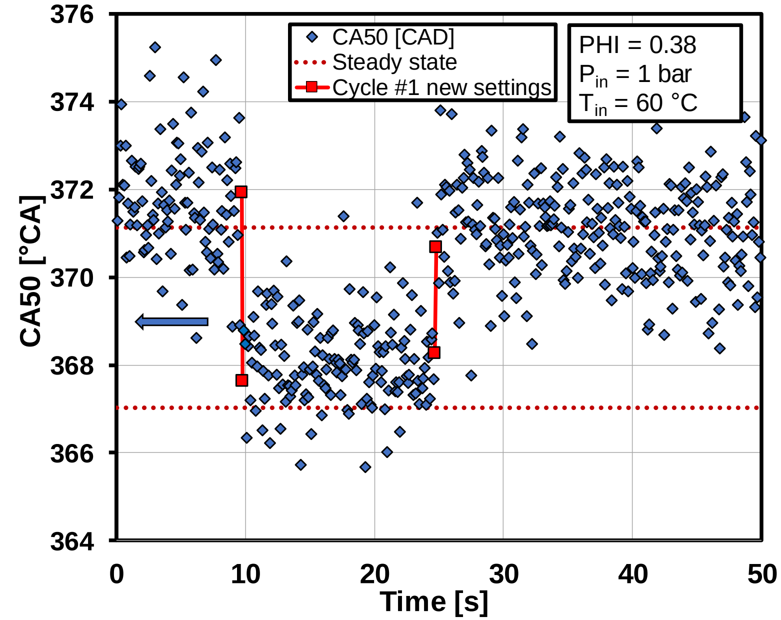
DDI-PFS Provides Next-Cycle CA50 Control

- Retard timing of 2nd-DI fueling pulse to increase fuel stratification and advance CA50. Return to original timing in 15 s.
  - Top plot: one-second averages of CA50
  - Bottom plot: CA50 of each cycle

- **DDI-PFS changes CA50 from one cycle to the next.**

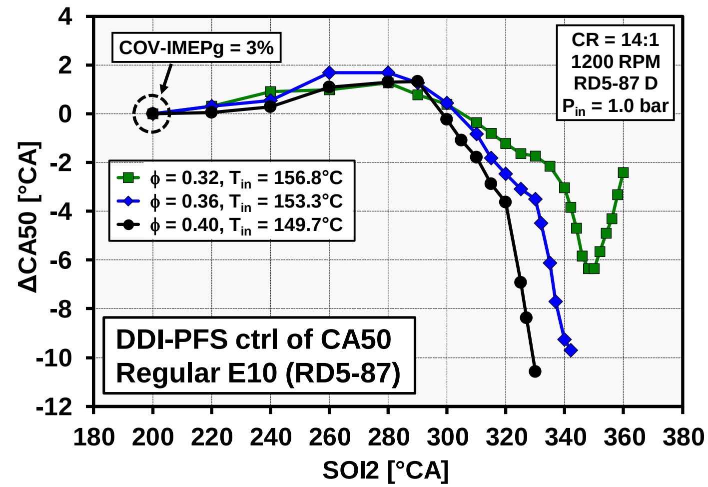
- Can apply DDI-PFS alone or combine with AMFI or another technique such as thermal management, exhaust rebreathe, etc. for control over a wider range.

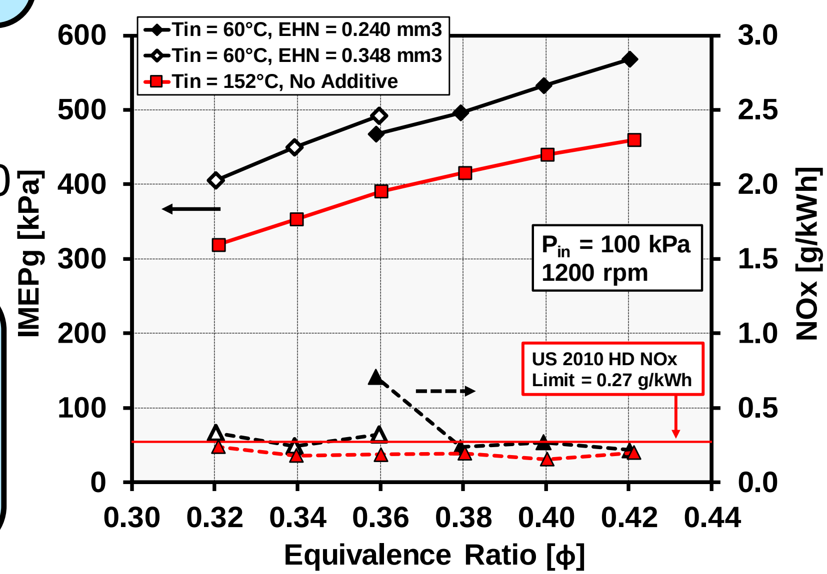




DDI-PFS Control Through a Fueling Sweep

- **DDI-PFS** can provide next-cycle CA50 ctrl over a wide range for ϕ = 0.32, 0.36, 0.40
- Is control sufficient to compensate for a significant change in load with a constant T_{in}, as would occur during a rapid transient ?
- For **P_{in}= 1 bar, no additive** ⇒ Reduce fueling starting from ϕ = 0.42, SOI2 = 200 (well mixed)
  - As ϕ reduced, CA50 becomes too retarded ⇒ Compensate by retarding SOI2 to ➚strat.
- DDI-PFS maintains good performance for
  ⇒ IMEPg = 460 → 319 kPa (> 30% change)
  ⇒ NOx < US 2010 HD limit
  ⇒ PM below detection limit of smoke meter
- DDI-PFS control also works w/ AMFI system
  - NOx increases for ϕ = 0.36 ⇒ increase EHN to reduce req'd. stratification, ➘NOx US-2010
  - Example of combining DDI-PFS with AMFI.
- DDI-PFS can provide next-cycle control over a significant range ⇒ depends on op. conds.
- Combine w/ another technique such as AMFI or thermal mgt. for control over a wide range.



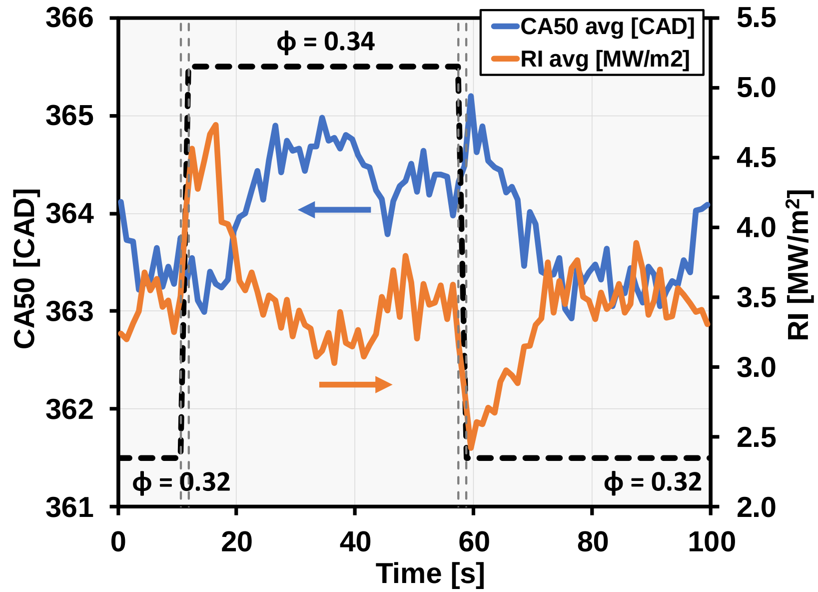


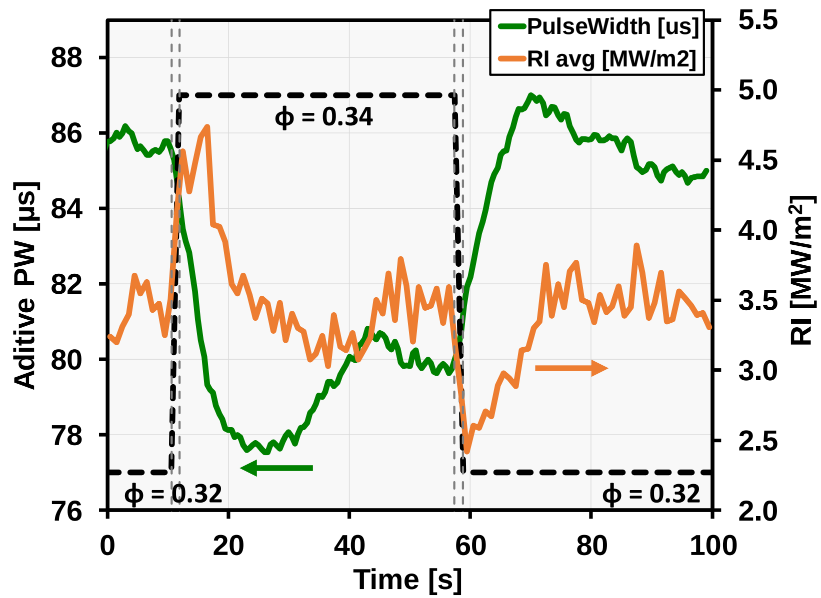
Adapting LTGC Lab for Transient-Test Capability
Initial Effort – Closed-Loop CA50 Control with AMFI

- Established a closed-loop control system
  ⇒ **Plots show an initial shakedown test**
- Analyze cylinder pressure to obtain CA50, CA10, Ringing Intensity (RI), etc.
  ⇒ Example controls to RI = 3.5 MW/m^2
- PID control algorithm adjusts additive pulse width (PW) to change charge reactivity to maintain RI = 3.5 MW/m^2 as fueling is varied from ϕ = 0.32 → 0.34 → 0.32

  <u>At 11 s</u>, manually ↗ϕ from 0.32 → 0.34
  – RI increases ⇒ control system reduces additive PW ⇒ CA50 becomes more retarded ⇒ reduces RI to ~3.5

  <u>At 58 s</u>, manually ↘ϕ from 0.34 → 0.32
  – RI decreases ⇒ control system increases additive PW ⇒ CA50 becomes more advanced ⇒ increases RI to ~3.5





- **Initial tests show ctrl system works well**
  ⇒ Next steps: test system over wider range and faster transients
- Also applicable to control with DDI-PFS or a combination of control methods.

Response to Reviewer Comments

- **Several reviewer comments made strong positive statements about the overall program as well about some of the individual studies, for example: "the project is very well developed"; "the project team has an excellent group of collaborators"; "surrogate kinetic work is very good and important"; "accomplishments and progress in this program are quite remarkable. . .".**
  - We have worked hard to tackle many critical barriers related to LTGC and greatly appreciate this feedback.
- **With respect to the AMFI system, there were many positive comments, such as "using an ignition improving additive may finally address the combustion phasing problem". However, there were concerns about whether the time response could be made sufficiently fast.**
  - We appreciate the reviewers' positive comments. ⇒The current setup was for an initial "proof-of-concept" to show that AMFI can control combustion phasing over a range of conditions, that had to be completed before our LDRD (internal funding) ended (see slide 14). AMFI control is inherently fast because it adjusts the additive each engine cycle, and in a commercial application the OEM would work with the injector manufacturer to keep dead volume low. Nevertheless, it is important to demonstrate the speed capability of AMFI, so we have designed a system with a much smaller dead vol. (slide 14) & will begin fabrication soon.
- **Multiple reviewers appreciated the new collaboration with SUNY-Stony Brook and strongly supported the addition of a CFD modeling effort to this program. However, some reviewers wondered why ANL was not involved in this CFD work.**
  - We agree that the CFD work is a valuable addition to this program and thank our partners at Stony Brook. ANL also has considerable expertise with CONVERGE CFD, and we talked with them about modeling our engine. However, they were working on several other projects & could not work on ours in the near future.
- **A reviewer wondered why we were pursuing the AMFI system if the engine would likely have a spark plug for SI operation at high loads in LD applications.**
  - Spark-assisted LTGC/HCCI has been pursued for nearly two decades without resulting in a practical engine. Also, our own studies show that flame speeds are too low for robust spark-assist without enrichment near the spark plug which typically leads to unacceptable NOx emissions.

Collaborations

- Project is conducted in close cooperation with U.S. Industry through the **Advanced Engine Combustion (AEC) Working Group**, under a memorandum of understanding (MOU).
  - Twelve OEMs, Three energy companies, Six national labs, & Several universities.
- **General Motors:** Bimonthly internet meetings ⇒ presentations and in-depth discussions of recent research. Support for GDI injectors & spark ignition system.
- **Cummins:** Engine hardware support
- **Hyundai-Kia America Tech Center, Inc. (HATCI):** Establishing a collaboration to support their LTC engine project & to apply AMFI and DDI-PFS control techniques.
- **SUNY-Stony Brook:** Collaboration for CFD-LES modeling of our LTGC engine.
- **Univ of Connecticut:** Collaborated on development of skeletal mechanism for CFD.
- **LLNL:** Provided engine data to LLNL for validation of their detailed chemical-kinetic mechanism for gasoline. Collaborated w/ LLNL to add EHN chemistry to this mech.
- **ANL:** Comparison of our data w/ CFR-engine data, & Autonomie evals. later this FY

DOE-OVT Project is also leveraged through 2 con-current research efforts.

- **Co-Optima Fuels Project:** Separately funded project on advanced fuels for LTGC and mixed-mode engines.
- **Chevron:** Funds-in project on improved petroleum-based fuels for LTGC.

Remaining Challenges and Barriers

- Combustion-timing control remains a key barrier that still lacks sufficient understanding and technical development.
- **AMFI system can control combst. timing over wide range of conds.**
  - Control is inherently very rapid, but need to engineer a practical system with faster response $\Rightarrow$ development of a faster system is underway.
- Development of methods for robust autoignition at low loads (IMEP ~2 bar) that give good combustion efficiency and low NOx.
  - AMFI combined with late single-DI fueling is promising.
  - Research is needed on improved late-injection and mixing strategies.
- Improved modeling of fuel-injection, CFD, & skeletal chemical-kinetics, with validation against measured in-cylinder fuel distributions & combust.
- Improved understanding of how intake flows interact with vaporizing fuel sprays to form charge mixture & how these flows produce thermal strat.
  - Combine with studies of single- and multiple-injection strategies.
- Improved understanding of fuel effects, additive (EHN) chemistry, and how EHN interacts with various fuel components to enhance autoignition.
- Understand performance of AMFI & other techniques on multi-cyl. engines.

Future Research

Any proposed future work is subject to change based on funding levels

- **Faster response time for AMFI system** and transient testing.
  - Complete new setup with reduced dead volume for rapid control.
  - Verify performance of new AMFI system over a range of conditions.
  - Upgrade closed-loop control system for the faster AMFI system.
- **Investigations to further improve low-load performance** using AMFI system combined with late Single-DI fueling.
  - New fuel-supply system being built to increase P-injection from 175 to 300 bar for improved stratification, higher CR=16:1, simulated exhaust rebreathe, etc.
  - Potential to improve cold-start by combining late S-DI fueling with AMFI.
- **Optical engine measurements of fuel distributions** to improve stratification techniques and to validate LES-CFD (new head mods. complete in FY19).
- **Continue LES-CFD modeling**, particularly for late Single-DI at low loads $\Rightarrow$ in collaboration with SUNY-Stony Brook.
- Finish adding EHN chemistry to LLNL mechanism, validate, & apply to AMFI.
  - Determine how EHN effectiveness varies with operating parameters & fuel comp.
- **Collaborate with Hyundai-Kia America** to support their LTC engine project, and to apply AMFI control and advanced DDI-PFS and late Single-DI injection strategies to their engine.

Summary

Relevance

- LTGC can provide efficiencies at or above diesel engines with low NOx & soot
  - Multi-mode for LD, use LTGC up to ~10 bar IMEPg, then switch to boosted SI for high loads.
  - Full-time for MD/HD, same strategies as LD to ~10 bar, loads to 20+ bar IMEPg; lower-cost vs. diesel.
- A rapid CA50 control system is required, & robust perform. over the map including low loads.

Approach

- Combine metal- and optical-engine experiments with CHEMKIN and CFD modeling.
- Expand understanding of AMFI system for improved CA50 control & greater operating range.
- Pursue techniques for increasing the speed of CA50 control and ability to study transients.
- Collaborate w/ SUNY-SB to apply CONVERGE-CFD to study stratified-charge LTGC combst.

Accomplishments

- Showed how changes in T_{in} and the use of EGR affect the AMFI control system.
- Applied AMFI combined with Single-DI charge stratification to extend operation to low loads $\Rightarrow$ achieved IMEPg = 2 bar with a Thermal Eff. = 37% (potential for further improvement).
- Developed a new design for the AMFI system for rapid response.
- Established closed-loop ctrl system & demonstrated with AMFI $\Rightarrow$ Initial step to study transients
- Investigated factors affecting DDI-PFS CA50 ctrl for both straight & EHN-additized fuel, and $\Rightarrow$ Demonstrated DDI-PFS control for a ~30% load change, while maintaining low NOx.
- Collaborated w/ U. Conn. to develop & validate a skeletal mech. to allow combst. in LES-CFD.
- Collaborated with SUNY–Stony Brook to apply LES-CFD to understand changes in mixture formation with DDI-PFS, & validated overall performance w/ combust. using new skeletal mech.
- Completed a study of the cause of ϕ-sensitivity & implications for fuel composition $\Rightarrow$ published
- Initiated a collaboration with Hyundai-Kia America to assist their LTC engine project.

Collaborations: Multiple collaborations are listed on Collaborations slide.

Future Research: Plans are outlined on Future Research slide.

Acknowledgement

- This work was performed at the Combustion Research Facility, Sandia National Laboratories, Livermore, CA.

  Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Technical Backup Slides

Improving Facility and Capabilities

Several upgrades to our facility and capabilities are underway or have been recently completed.

- Changing AMFI setup for faster control.
- Increasing GDI fuel-injection pressure capability from 175 to 300 bar.
  $\Rightarrow$ For better performance with fuel stratification, particularly for late single-DI fueling to improve low-load operation.
- Established closed-loop control system $\Rightarrow$ automated transient studies.
- New optical-engine head to match current metal-engine head.
  $\Rightarrow$ Modifications underway and on-track to complete by end of FY19.
- Adding EHN reaction chemistry to the LLNL detailed mechanism.
- Improved the NOx chemistry of the LLNL detailed mechanism.
- Developed skeletal mechanism for gasoline for use with CFD modeling.
  $\Rightarrow$ Validated against well-mixed LTGC (HCCI) data.
  $\Rightarrow$ Recently upgraded for better performance with richer ($\phi > 0.8$) mixtures.

AMFI Works Well at Conditions Requiring EGR

- Fuel reactivity increases with boost, so additive will approach zero at P_{in} ≈ 1.4 bar, so need EGR above this P_{in}.
  - Constant T_{in} = 60°C and RI = 5 MW/m^2
- At P_{in} = 1.6 bar, EGR is required to prevent overly advanced CA50 even without additive.
  ⇒ O_2 = 18% for RI = 5 MW/m^2
- Additive increases fuel reactivity, so must increase EGR for AMFI to control CA50.
- Incr. EGR to 14.3% O_2 reducing reactivity ⇒ 0.12 mm^3 of EHN restores RI = 5.
- Further increase EGR to 13.4% O_2 ⇒ Compensate by increasing additive to hold RI = 5 MW/m^2. ⇒ **Smooth tradeoff between intake O_2 and additive**.
- Increasing the additive increases the fuel's ϕ-sensitivity ⇒ broadens HR so CA50 must be advanced to obtain RI = 5 MW/m^2.